

Central exclusive diffractive Higgs boson production in hadron-nucleus and nucleus-nucleus collisions at the LHC

E. Levin^{*} and J. Miller[†]

Department of Particle Physics, School of Physics and Astronomy

Raymond and Beverly Sackler Faculty of Exact Science

Tel Aviv University, Tel Aviv, 69978, Israel

ABSTRACT: In this paper, it is shown that in hadron-nucleus and nucleus-nucleus collisions, the main source for central exclusive diffractive Higgs production is photon-photon fusion. At the LHC energy, the total cross section for this process is about 0.6 pb (for proton-gold scattering), and 3.9 nb (for gold-gold collision) while the gluon-gluon fusion leads to the value of the cross section for CED Higgs production which is about 0.1 nb and 3.9 pb respectively.

KEYWORDS: Higgs production, BFKL Pomeron, Survival probability, Glauber approach .

^{*}Email: leving@post.tau.ac.il, levin@mail.desy.de;

[†]Email: jeremymiller@london.com, jeremymi@post.tau.ac.il;

The most important discovery, that everybody expects at the LHC, is the discovery of the Higgs boson. The exclusive process which has the best experimental signature, as far as we know, is the central exclusive diffractive (CED) Higgs production. Having two large rapidity gaps between the Higgs and the recoiled particles (nuclei), this process has the minimal background from the QCD processes without the Higgs. However, the total cross section for CED Higgs production turns out to be very small for proton -proton interactions: about 3 fb for gluon-gluon fusion (see detailed estimates by the Durham group in Ref. [1]) and about 0.1 fb for $\gamma\gamma$ fusion, (see Ref.[2]).

In this letter we consider CED Higgs production in collisions with nuclei, and we will show that the gluon-gluon fusion even in proton-nucleus collisions leads to a very small cross section, while $\gamma\gamma$ fusion gives a valuable cross section (about 0.64 pb for proton-gold collision at the LHC). This conclusion stems from a striking difference in the value of the survival probabilities for these two processes, which is negligibly small for gluon-gluon fusion, and of the order of unity for $\gamma\gamma \rightarrow$ Higgs process.

The CED Higgs production is a process with two large rapidity gaps (LRG), between the recoiled particles and the Higgs boson. Namely, this reaction for proton -nucleus ($p A$) collisions looks as follows

$$p + A \rightarrow p + [LRG] + \text{Higgs} + [LRG] + A \quad (1)$$

Since the mass of the Higgs boson (M_H) is expected to be large (say 100 GeV or more), the typical distances in a one parton shower interaction is short ($r \propto 1/M_H \ll \Lambda_{QCD}$), and perturbative QCD can be used to calculate the amplitude for the reaction of Eq. (1) (see Refs.[1, 3]). However, the processes of two partonic shower production will ruin the two LRG signature, as it is shown in Fig. 1. Therefore, we need to multiply the cross section for the processes shown in the diagrams of Fig. 1-a and Fig. 1-c, by the damping factor that we call the survival probability [4]. Generally speaking, we do not have a scale of hardness for the two partonic shower production, and both short and long distances can contribute to the calculation of the survival probability. In the case of hadron-hadron collisions, the most difficult part of the calculation is related to the long distance processes, for which we do not have a theory and have to rely on the models for the value of the survival probability (see Refs.[5, 6] and references therein). However, we would like to mention here that the short distance processes for which we do have a theory (high density QCD), can give a large contribution to the value of the survival probability (see Refs.[3, 7]).

For hadron-nucleus and nucleus-nucleus collisions, the main source of the shadowing corrections is the Glauber rescattering off different nucleons. The simple formula for the survival probability, in this takes the following form. [4]

$$\langle |S^2| \rangle = \frac{\int d^2b A_H(b) \exp(-\Omega(b, s))}{\int d^2b A_H(b)} \quad (2)$$

where $A_H(b)$ is the impact parameter image of the hard amplitude shown in Fig. 1-a and Fig. 1-c, and

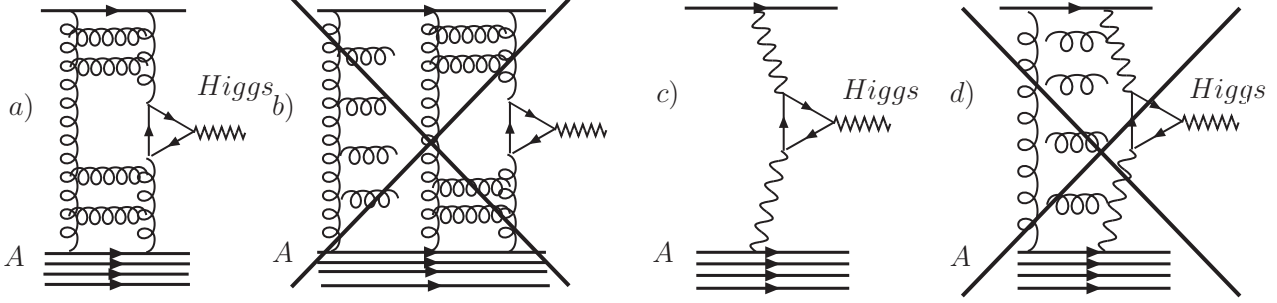


Figure 1: CED Higgs production from one parton shower (Fig. 1-a and Fig. 1-c) and two parton shower interaction (Fig. 1-b and Fig. 1-d) that ruin the large rapidity gap signature of the reaction of Eq. (1).

the opacity Ω for proton-nucleus scattering is equal to

$$\Omega(s, b) = \sigma_{tot}(\text{proton-proton}, s, b) T_A(b) \quad \text{with} \quad T_A(b) = \int \rho_A(r) dz \quad (3)$$

where $\rho_A(r)$ is the density of nucleons in a nucleus with mass number A , and z is the longitudinal coordinate in the beam direction. σ_{tot} is the total cross section of the proton-proton interaction at the energy of interest. It should be mentioned that Eq. (2) is exact in the Glauber approach and, therefore, for hadron-nucleus and nucleus-nucleus interaction we do not have uncertainties in the formula for survival probability unlike for the nucleon-nucleon collisions.

The nucleon density is given by the Wood-Saxon parametrization (see Ref.[8]), in which it has the form

$$\rho(b) = \frac{\rho_0}{1 - \exp\left(\frac{r-R_A}{h}\right)} \quad \text{with} \quad \int d^3r \rho(r) = A \quad (4)$$

$r = \sqrt{b^2 + z^2}$ and $R_A = r_0 A^{1/3}$ with $r_0 = 1.09 \text{ fm}$ while h does not depend on A . For the gold $R_{Au} = 6.38 \text{ fm}$ and $h = 0.535$ (see Ref. [8]). ρ_0 has a physical meaning of the nucleon density in the nuclear matter and it can be found from the normalization, given in Eq. (4), which leads to $\rho_0 = 0.17 \text{ fm}^{-3}$.

Taking $\sigma_{tot}(\text{proton-proton}, s, b) = 110 \text{ mb}$ at the LHC energy [9], one can see that $\Omega(s, b)$ in Eq. (3) is equal to

$$\Omega(s_{LHC}, b) = 11 \text{ fm}^2 T_A(b) \quad (5)$$

The b dependence of $\exp(-\Omega)$ for proton-gold collision is shown in Fig. 3. The striking difference between the value of the survival probability for CED Higgs production for gluon-gluon fusion and $\gamma - \gamma$ fusion stems from the quite different behavior of the hard amplitudes A_H for these two processes. In the case of gluon fusion, the hard amplitude decreases steeply with $b > R_A$, while for photon fusion this

amplitude only slowly falls down with increasing b . This qualitative difference is obvious from Fig. 3, where the normalized A_H for both processes are plotted. The normalized \tilde{A}_H is defined as *

$$\tilde{A}_H(b) \equiv \frac{A_H(b)}{\int d^2b A_H(b)} \quad (6)$$

In the case of gluon-gluon fusion, it is better to say that for Pomeron-Pomeron ($\mathbb{P}\mathbb{P}$) fusion, the hard amplitude takes the form (see Fig. 2-a)†

$$A_H^{\mathbb{P}\mathbb{P}}(Q) = \int d^2q_{1,\perp} \int d^2q_{2,\perp} M(\mathbb{P}\mathbb{P} \rightarrow H; \vec{q}_1, \vec{q}_2) M^*(\mathbb{P}\mathbb{P} \rightarrow H; \vec{q}_1 + \vec{Q}, \vec{q}_2 - \vec{Q}) \quad (7)$$

where the amplitude $M(\mathbb{P}\mathbb{P} \rightarrow H; \vec{q}_1, \vec{q}_2)$ for CED Higgs production through $\mathbb{P}\mathbb{P}$ fusion takes the form [1, 3]

$$M(\mathbb{P}\mathbb{P} \rightarrow H; \vec{q}_1, \vec{q}_2) = \frac{2}{9} A s G_p(q_1^2) G_A(q_2^2) \int \frac{d^2q_\perp}{q_\perp^2} \frac{(\vec{q}_{1,\perp} - \vec{q}_\perp) \cdot (\vec{q}_{2,\perp} + \vec{q}_\perp)}{(\vec{q}_{1,\perp} - \vec{q}_\perp)^2 (\vec{q}_{2,\perp} + \vec{q}_\perp)^2} 8\alpha_s^2(q^2)$$

where $A = \frac{2}{3} \frac{\alpha_S G_F^{1/2} 2^{1/4}}{\pi}$ (8)

In Eq. (8), one takes into account the proton couplings to the gluon ladder (see Fig. 2), by including the two gluon form factors ($G_p(q_1^2)$ and $G_A(q_2^2)$) for the gluon density in the proton and the nucleus respectively. As it was shown in Ref. [1], the momentum \vec{q}_\perp of the t -channel gluon in Fig. 2-a turns out to be large ($q_\perp \ll 1/R_p$ where R_p is the radius of the proton. In the Glauber approach, we consider $R_A \gg R_p \gg 1/q$, and therefore, the Q dependence of Eq. (7) is determined by

$$\int d^2q_{2\perp} G_A(q_{2\perp}^2) G_A((\vec{q}_{2\perp} + \vec{Q})^2) = \int d^2b e^{i\vec{Q} \cdot \vec{b}} T_A^2(b) \quad (9)$$

Eq. (9) means that the amplitude $A_H(b)$ in Eq. (2) is proportional to $T_A^2(b)$, and the survival probability is equal to

$$\langle |S^2| \rangle_{GG \rightarrow H} = \frac{\int d^2b T_A^2(b) \exp(-\Omega(b))}{\int d^2b T_A^2(b)} \quad (10)$$

Fig. 3 shows why the value of $\langle |S^2| \rangle_{GG \rightarrow H}$ should be small, since only in the vicinity of $b \rightarrow R_A$ does the numerator contribute significantly in Eq. (10). The calculation gives $\langle |S^2| \rangle_{GG \rightarrow H} = 8 \times 10^{-4}$ for proton-gold collisions at the LHC energy.

The situation with the hard amplitude for photon fusion is quite the opposite, namely it is a smooth function of b , which only slowly decreases at large values of b . Therefore, the ratio of Eq. (2) can be

*We will use below the notation A_H instead of \tilde{A}_H , but we hope that it will not cause any confusion.

†Pomerons in Fig. 2-a correspond to the gluon ladders.

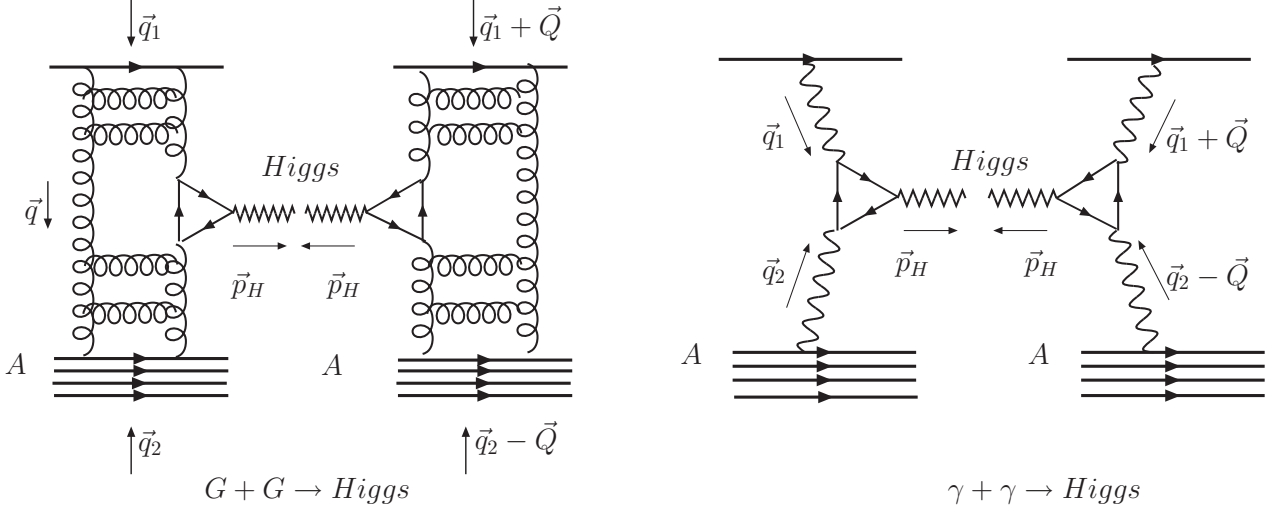


Figure 2: The amplitude $A_H(Q)$ for CED Higgs production due to gluon-gluon and $\gamma - \gamma$ fusion.

evaluated in the following way for CED Higgs production through $\gamma - \gamma$ fusion

$$\langle |S^2| \rangle_{\gamma\gamma \rightarrow H} = \frac{\int d^2b A_H(b) \exp(-\Omega(b, s))}{\int d^2b A_H(b)} \approx \frac{\int_{R_A^2}^\infty db^2 A_H(b)}{\int d^2b A_H(b)} \quad (11)$$

It is clear from the discussion above that we need to know the dependence of the hard amplitude on b at large b , which is intimately related to the behavior of this amplitude at small values of Q (see Fig. 3). The required hard amplitude can be written in the form

$$A_H(Q) = \int d^2q_{1,\perp} \int d^2q_{2,\perp} M(\gamma\gamma \rightarrow H; \vec{q}_1, \vec{q}_2) M^*(\gamma\gamma \rightarrow H; \vec{q}_1 + \vec{Q}, \vec{q}_2 - \vec{Q}) \quad (12)$$

where (see Ref.[2] and references therein):

$$M(\gamma\gamma \rightarrow H; \vec{q}_1, \vec{q}_2) = \frac{4\pi\alpha_{\text{em}}}{q_{1,\perp}^2 q_{2,\perp}^2} F_A(q_{2,\perp}^2) F_p(q_{1,\perp}^2) \frac{2s}{M_H^2} 4q_{1,\perp}^\mu q_{2,\perp}^\nu A_{\mu\nu} \quad (13)$$

with

$$A^{\mu\nu} = \frac{8}{27} \frac{\alpha_{\text{em}} G_F^{\frac{1}{2}} 2^{\frac{1}{4}}}{\pi} \left\{ q_1^\mu q_2^\nu - \frac{M_H^2}{2} g^{\mu\nu} \right\} \equiv A \left\{ q_1^\mu q_2^\nu - \frac{M_H^2}{2} g^{\mu\nu} \right\} \quad (14)$$

In Eq. (13) $F_A(q_{2,\perp}^2)$ and $F_p(q_{1,\perp}^2)$ stand for the electromagnetic form factors of the nucleus and the proton, respectively. In the region of small Q , (namely $Q < q_1$ and q_2), Eq. (12) can be re-written as

$$A_H(Q) = 4\pi^2 s^2 (4\pi\alpha_{\text{em}})^2 A^2 \int_{Q^2}^{4/R_p^2} \frac{dq_{1,\perp}^2}{q_{1,\perp}^2} \int_{Q^2}^{4/R_A^2} \frac{dq_{2,\perp}^2}{q_{2,\perp}^2} = C \ln(Q^2 R_A^2/4) \ln(Q^2 R_p^2/4) \quad (15)$$

where the coefficient C is defined such that C absorbs all factors, since they do not contribute in the calculation of the survival probability (see Eq. (2)). The hard amplitude in impact parameter space is equal to

$$\begin{aligned} A_H(\gamma\gamma \rightarrow H; b) &= \frac{1}{(2\pi)^2} \int d^2Q e^{-i\vec{b}\cdot\vec{Q}} A_H(Q) \\ &= \frac{C}{(2\pi)^2} 2\pi \int dQ^2 J_0(bQ) \ln(Q^2 R_A^2/4) \ln(Q^2 R_p^2/4) \\ &\xrightarrow{1/Q_{\min} > b > R_A/2} \frac{C}{(2\pi)^2} \pi \left\{ 2 \frac{\ln(4b^2/R_A^2)}{b^2} + \ln(R_A^2/R_p^2) \right\} \end{aligned} \quad (16)$$

where $Q_{\min} = mM_H/\sqrt{s}$ (see for example Ref.[2]). In the region of small b , we need to derive the exact expression of Eq. (13), and the behavior of the hard amplitude versus b is shown in Fig. 3.

Using Eq. (11), we can estimate the value of the survival probability which turns out to be equal to $0.8 \div 0.85$ in proton-gold collisions.

From our estimates for the survival probability, we can obtain the value of the cross section for CED Higgs production. Indeed,

$$\begin{aligned} \sigma_{pA}(G + G \rightarrow H; s, Y_H) &= \sigma_{pp}(G + G \rightarrow H; s, Y_H) A^2 \langle |S^2(G + G \rightarrow H)| \rangle \\ &= 33 \times \sigma_{pp}(G + G \rightarrow H; s, Y_H) ; \end{aligned} \quad (17)$$

$$\begin{aligned} \sigma_{pA}(\gamma + \gamma \rightarrow H; s, Y_H) &= \sigma_{pp}(\gamma + \gamma \rightarrow H; s, Y_H) Q_A^2 \langle |S^2(\gamma + \gamma \rightarrow H)| \rangle \\ &= 5 \times 10^3 \times \sigma_{pp}(\gamma + \gamma \rightarrow H; s, Y_H) ; \end{aligned} \quad (18)$$

where Q_A (A) is the number of protons (nucleons) in the nucleus and Y_H is the rapidity of the Higgs boson. The numbers in Eq. (17) and Eq. (18), are given for proton-gold collisions at the LHC energy. One can see, that the cross section for gluon fusion is extremely small, while in the case of photon fusion, it can lead to a measurable cross section. Taking for the value of $\sigma_{pp}(\gamma + \gamma \rightarrow H; s, Y_H) = 0.12 \text{ fb}$ (see Ref.[2]) we obtain for $\sigma_{pA}(\gamma + \gamma \rightarrow H; s, Y_H) = 0.64 \text{ pb}$ at the LHC energy. For gluon-gluon fusion we have $\sigma_{pp}(G + G \rightarrow H; s, Y_H) = 3 \text{ fb}$ which leads to the value of $\sigma_{pA}(G + G \rightarrow H; s, Y_H)$ for proton-gold collision at the LHC energy about 100 fb , which is in 6 times smaller than the cross section for photon fusion.

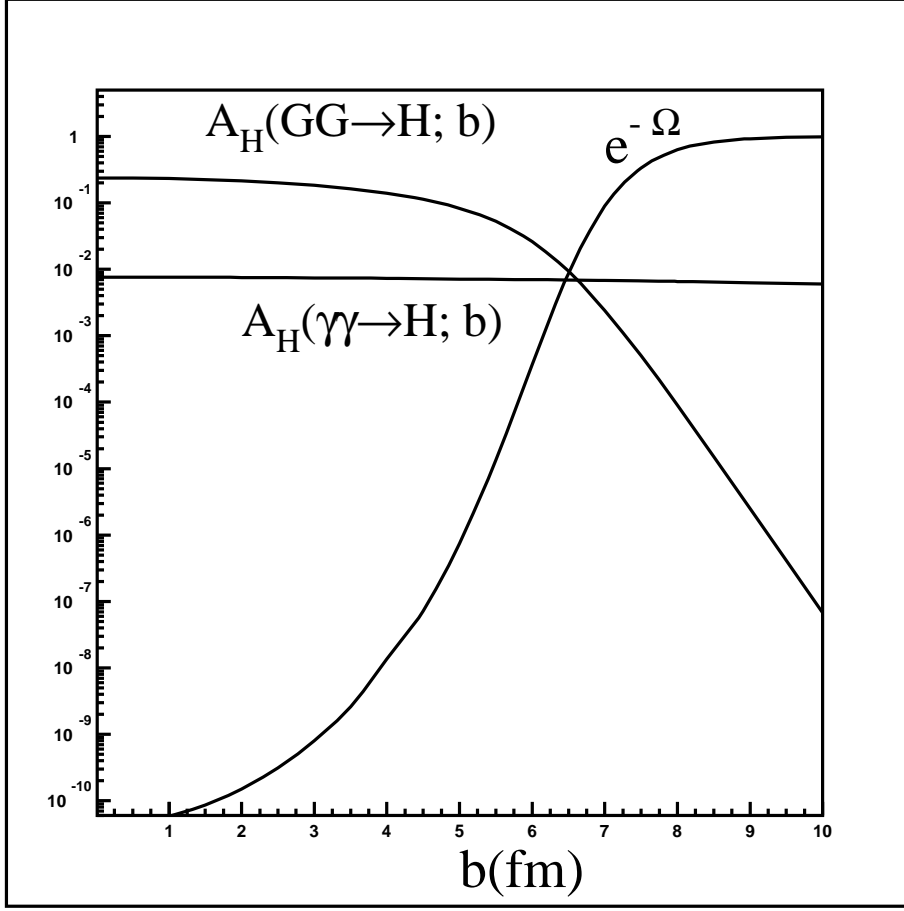


Figure 3: The damping factor $\exp(-\Omega)$, and hard amplitude $A_h(b)$ for *gluon + gluon* \rightarrow *Higgs* and $\gamma + \gamma \rightarrow$ *Higgs* fusions versus impact parameter b in the model of Eq. (5) for the density of nucleons in a nucleus.

The same pattern in estimates can be seen for CED Higgs production in ion-ion collisions. In Eq. (3) we need to replace $T_A(b)$ by the overlapping integral of profile functions for two nuclei, namely

$$T_A(b) \longrightarrow T_{A_1 A_2} = \int d^2 b' T_{A_1}(b'^2) T_{A_2}((\vec{b} - \vec{b}')^2) \quad (19)$$

For gluon-gluon fusion the hard amplitude $A_H(b)$ has the form

$$A_H(b) \propto \int d^2 b' T_{A_1}^2(b'^2) T_{A_2}^2((\vec{b} - \vec{b}')^2) \quad \text{which is a Fourier image of} \quad (20)$$

$$\int d^2 q_{1,\perp} G_{A_1}(q_{1,\perp}) G_{A_1}(\vec{q}_{1,\perp} + \vec{Q}) \times \int d^2 q_{2,\perp} G_{A_2}(q_{2,\perp}) G_{A_2}(\vec{q}_{2,\perp} + \vec{Q})$$

The survival probability for gluon fusion is small ($\approx 8.16 \cdot 10^{-7}$, for gold-gold scattering). This survival probability leads to the value of the cross section in the case of gold - gold scattering $3 \text{ fb} \times 8 \cdot 10^{-7} \times A^2 =$

3.92 pb. However, for photon fusion the value of the survival probability does not change too much, while the cross section is proportional to Q_A^4 , leading to an enhancement in the value of the cross section for CED Higgs production in gold-gold collisions at the LHC, by a factor of 3.9×10^7 . In other words, the value for $\sigma_{AA}(\gamma + \gamma \rightarrow H; s, Y_H) \approx 3.9$ nb for gold-gold collisions.

Therefore, we can conclude that central exclusive diffractive Higgs production in the case of hadron-nucleus collisions, as well as in the case of nucleus-nucleus collisions, goes through the reaction $\gamma + \gamma \rightarrow \text{Higgs}$, and can reach a rather significant value for the LHC energies: $\sigma_{AA}(\gamma + \gamma \rightarrow H; s, Y_H) \approx 3.9$ nb for gold-gold collisions, and $\sigma_{pA}(\gamma + \gamma \rightarrow H; s, Y_H) \approx 0.64$ pb. The advantage of the photon fusion reaction, is the fact that we can calculate its cross section without any theoretical uncertainty. This makes the collision with nuclei a valuable tool for the discovery of the Higgs boson at the LHC.

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